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Observations of Stars in H II Regions : Spectral Classification and UBV Photometry

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UBV photometry and spectral types are presented for stars which may be the exciting stars of H II regions in the southern hemisphere. Attention is drawn to stars which belong to five open clusters and also to possible Wolf-Rayet members of the clusters.

I. INTRODUCTION II. UBV PHOTOMETRY

THE importance of H II regions to the study of the spiral structure of our Galaxy is well known. In order to improve our knowledge of the distances to these regions, an extensive program is being undertaken to provide basic data for the exciting stars. This paper presents the results of spectral classification and *UBV* photometry of stars in southern H II regions. The stars were chosen from lists of stars in H II regions by several stars including Bok, Bester, and Wade (1955), Gum (1955), Hoffleit (1956), Le Marne and Lyngå (1968), Münch (1955), Sharpless (1959), and from a comparison of the positions and sizes of H II regions with the positions of OB stars found in the surveys by Graham and Lyngå (1965), Klare and Szeidl (1966), Lyngå (1964), Lyngå (1968a), and Nassau, Stephenson and MacConnell (1965). The spectroscopic observations were made at the Radcliffe Observatory, Pretoria, and the *UBV* photometry was carried out at the Royal Observatory, Cape of Good Hope.

The observations were all made during the period 20 February through 13 March 1970 with the one-meter (40-inch) Elizabeth reflector using the Cape photometer and following the conventional Cape procedure. Since the observational and reduction procedures were essentially those recently described by Clabe, Evans, and Jones (1969), and Hill (1970), they will not be repeated here. The stars for which *UBV* observations were made are listed in Table I. The few stars not identified by their HD or Durchmusterung numbers are identified through references in the notes to the table. The eighth column gives *N*, the number of nights on which the star was observed photometrically. The dispersion, *S*, or standard error of a single observation in *V* is listed in column 9 (units are 0.01 mag) for stars with three or more observations. A designation of the H II regions with which the star is supposed to be associated is given in column 10. BW numbers refer to the catalogue of Bok, Bester, and Wade (1955), G to

TABLE I. Data on stars for which UBV photometry was obtained.

Star	R.A. (1900)	Dec.	Sp.	V	B - V	U - B	N	S	Region	Notes
HD 48691	06 ^h 39 ^m 5	+00°42'	B0.5 IV*	7 ^m 83	+0 ^m 09	-0 ^m 80	5	2	S284	
BD +00°1576	39.7	+00 44	O9 III	9.24	+0.45	-0.61	4	2	S284	
HD 48807	40.1	+00 04	(B7 Ib)*	7.02	+0.41	-0.40	5	2	S284	
LS VI +00°19	40.4	+00 22	OB*	11.40	+0.46	-0.56	5	2	S284	(2)
BD -00°1491S	50.1	-00 26	B0 V	12.05	+0.26	-0.65	4	5	S285	(1)
LS VI -04°19	54.5	-04 41	B0 IV	10.76	+0.46	-0.51	5	2	S287	(2)
HD 53948	07 01.9	-12 33	B5*	9.72	+0.03	-0.50	2		S296	
HD 54025	02.2	-11 10	B5*	7.62	-0.02	-0.81	4	2	S296	
HD 54306	03.2	-11 46	B5*	8.79	0.00	-0.69	4	1	S296	
HD 54602	04.6	-10 11	O6*	6.22	+0.02	-0.91	4	2	S296	
HD 57370AB	15.8	-21 42	B0.5 V:	8.74	+0.08	-0.76	5	1	RCW 14	(3)
BD -21°1881	15.8	-21 43	B1 V	9.82	+0.06	-0.76	3	1	RCW 14	(4)
CP -35°2252AB	08 17.1	-35 54	K3	10.00	+1.31	+0.91:	4	3	G11	(5)
CP -40°2666	31.9	-40 19	B1 IV	9.86	+0.46	-0.42	5	4	NGC 2626	
HD 75724	46.5	-41 44	B0.5 V	7.70	-0.05	-0.78	6	1	G17	†
CP -43°3043	47.3	-43 28	O7.5	9.54	+0.87	-0.26	5	0	G18	
HD 75991	48.2	-47 12	B0.5 V	8.98	+0.13	-0.76	4	2	G21	
HD 76004	48.3	-43 47	B3 V	6.37	-0.15	-0.60	4	3	G18	†
HD 76031	48.5	-43 39	B1.5 II	8.99	+0.50	-0.44	5	2	G18	†
HD 76535	51.6	-47 02	O9.5 III	8.58	+0.40	-0.62	4	3	G21	(6)
CP -48°2166	59.0	-48 18	O8:	10.30	+0.76	-0.36	3	3	G25	†
HD 87643	10 01.1	-58 11	Bp*	8.74	+0.71	-0.40	6	7	RCW 47	
CP -58°1876AB	01.6	-58 41	OB*	10.86	+0.12	-0.14	4	2	RCW 47	(7)
HDE 302505	02.0	-58 16	B2*	9.54	+0.42	-0.60	5	2	RCW 47	CP -58°1886
HD 97499	11 08.0	-60 46	B0.5 V	9.22	+0.06	-0.78	4	2	G38a	(8)
CP -60°2641	08.0	-60 44	B0 V	10.88	+0.36	-0.72	2	4	G38a	(8)
HD 99898	24.4	-62 22	O9 V	9.34	+0.34	-0.64	6	4	G40	
CP -60°4312	12 44.4	-61 02	O9.5 V	10.74	+0.68	-0.33	4	3	G46	
HD 114122	13 03.3	-62 20	B1 lab	8.57	+0.59	-0.46	6	2	RCW 74	

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TABLE I (continued)

Star	R.A. (1900)	Dec.	Sp.	V	B-V	U-B	N	S	Region	Notes
HD 114478	05 ^m 6	-62°17'	B1 Ib	8 ^m 68	+0 ^m 49	-0 ^m 52	6	2	RCW 74	
HD 115316	11.3	-61 56	B1 V*	9.31	+0.23	-0.72	4	3	RCW 75	
HD 115345	11.5	-61 56	B8*	9.06	+0.24	-0.35	2	2	RCW 75	
HD 115455	12.1	-61 58	O8	7.99	+0.22	-0.77	4	2	RCW 75	(9)
CP -61°3576	12.2	-62 00	B0.5 V	9.48	+0.29	-0.67	5	2	RCW 75	(9,10)
CP -61°3579	12.2	-61 59	B2 V	10.46	+0.24	-0.67	2	2	RCW 75	(9)
CP -61°3581	12.3	-61 58	B2 V*	10.18	+0.24	-0.61	4	4	RCW 75	(9)
CP -61°3587	12.6	-62 03	B1 V*	10.72	+0.30	-0.54	4	2	RCW 75	(9)
CP -61°3598	13.0	-62 08	B2 Ib*	10.30	+0.84	-0.14	3	2	RCW 75	
HD 117704	26.9	-61 48	B1 III	8.90	+0.22	-0.62	4	2	RCW 78	
HD 117797	27.5	-61 54	O8†	9.19	+0.50	-0.56	3	2	RCW 78	
HD 119646	39.3	-61 57	B2 Ib*	6.61	+0.11	-0.72	4	1	RCW 80	
HD 122669	58.1	-62 01	B0.5 Ve	8.96	+0.38	-0.74	4	2	RCW 83	
HD 122691	58.2	-62 06	B0.5 Vne	9.20	+0.36	-0.76	4	1	RCW 83	
HD 124909	14 ^h 11.1	-60 26	B1 III	11.43	+0.28	-0.63	4	1	RCW 85	
Lynga ^a 63	12.3	-63 26	B1.5 III	11.43	+0.32	-0.56	4	5	RCW 84	(11)
HD 125206	12.8	-60 37	O9.5 Vne	7.92	+0.26	-0.71	4	1	RCW 91	
HD 134958	15 07.5	-57 48	B0.5 Vne	8.12	+0.32	-0.57	4	1	RCW 91	
HD 134959	07.5	-58 42	B2 Ia	8.10	+1.04	-0.09	3	2	BRW 28802	(12)
Pismis 20-11	07.5	-58 42	B0 Ia	10.60	+0.96	-0.30	2	3	BRW 28802	(12)
CP -54°6791	47.9	-54 21	O9.5 IV	10.39	+0.56	-0.48	4	3	G 49	
CP -50°9216	16 11.5	-50 39	B0.5 IV	11.02	+0.43	-0.29	4	2	RCW 106	
CP -50°9244	12.7	-50 45	O8*	10.67	+0.41	-0.15	2	2	RCW 106	
CD -45°11034	46.5	-45 08	O8.5	11.08	+0.89	-0.24	2	2	RCW 110	
CD -45°11051	47.4	-45 04	O8.5	10.96	+0.96	-0.10	2	2	RCW 110	
HDE 322422	50.4	-40 13	B0.5 III:e	9.75	+0.22	-0.47	2	2	G 56	†CP -40°7661
HDE 322417	52.0	-40 06	O5.5	10.10	+0.88	-0.33	2	2	G 56	† (13)
HD 153426	54.4	-38 03	O8.5	7.47	+0.14	-0.82	2	2	S2	
HD 153919	57.2	-37 42	O7*	6.56	+0.26	-0.74	2	2	S2	
HD 156468	17 12.6	-37 54	B1 Ve	7.76	+0.20	-0.58	2	2	S5	(14)
HDE 319788	19.8	-34 12	B2 III:	9.62	+0.50	-0.37	2	2	S11	CP -34°6825
HD 161853	42.8	-31 13		7.94	+0.23	-0.72	2	2	S15	

Notes to Table I

A dagger (†) in the notes column indicates that the spectral type was determined from plates in the Radcliffe files (not taken by the writer).

1. BD -00°14915: There are two stars (separation 15") to which the BD number may refer. The northern star is of later type. The southern star appears to be single at the telescope.
2. The IS VI numbers refer to the catalogue of Nassau, Stephenson, and MacConnell (1965).
3. HD 57370AB: Two stars of apparently equal brightness separated by about 6". In the cluster NGC 2367. The *U*BY observations refer to the combined light of the pair. Spectra taken with a star on either half of the slit show that the two stars are almost exactly equal in brightness and identical in spectral type, although the lines of one star are more diffuse than those of the other star.
4. BD -21°1881: also a member of NGC 2367.
5. CP -35°257A: is the brightest star in the small bright nebula NGC 2579 (for a picture see Westerlund and Henize 1966). The photometry given here refers to the combined light of this star and a star 10" to the south. On one night, measures of the bright component only gave $V=10.2$, $B-V=1.4$, $U-B=1.7$. It is obvious that component A with these colors and a spectral type of approximately K3 is not the exciting star of the nebula but component B may be. The latter star must be very blue to have altered the color from those given above to those in the table and it is approximately central in the nebula.

that of Gunn (1955), RCW to that of Rodgers, Campbell, and Whiteoak (1960), and S to that of Sharpless (1959).

The photometric observations were quite consistent from one night to the next as may be seen from the dispersions listed in Table I. The internal accuracy in ($B-V$) and ($U-B$) tends to be somewhat better than that in V ; the average dispersion estimated from four stars with six observations each being 0^m01 in either color. It should be noted that, due to poor seeing which appears to be general at the Cape, a photometer diaphragm size of 30 sec of arc or occasionally larger had to be used. In a few cases, faint companions or a

6. Two companions to HD 76535 approximately 15" and 30" away were both excluded in the photometry.
7. CP -58°1876A has a companion about 10 sec of arc away and approximately one magnitude fainter. Measures of component A on one night gave $V=11.10$, $B-V=+0.11$, $U-B=-0.21$.
8. There is bright nebulosity in the neighborhood of these two stars; CP -60°2641 was added to the original program for this reason. A small "hole" in the nebulosity is visible around this star on a Radcliffe direct photograph—possibly an indication that the star is associated with the nebula.
9. Members of the small cluster Stock 16.
10. CP -61°3576 has a faint companion about 10 sec of arc away. The ($B-V$) observations were not consistent from night-to-night ranging from +0.24 to +0.33.
11. Star number 63 in the OB catalogue of Lynga^a (1964).
12. HD 134959 is the brightest star in the cluster Pismis 20. This star plus three others including Pismis 20, No. 11 form a trapezium-like system with sides of approximately 12 sec of arc. Photometry of these stars is difficult, of course. For identification of No. 11 see the chart published by Lynga^a (1968).
13. The spectra of this star show very weak "r" characteristics. CP -40°7677.
14. Unpublished spectral type by Dr. A. D. Thackeray.

bright nebular background may have affected the photometry although care was taken to avoid these effects. A comparison between the photometry in Table I and that of five other observers was possible for 14 stars. The agreement was excellent for 13 of the stars with no systematic differences in either the magnitude or the colors. The dispersion or random error was 0^m015 in V and ($B-V$) and 0^m025 in ($U-B$). Observations of HD 134958 by Huag, Phleiderer, and Dachs (1966) gave $V=8.00$, $B-V=+0.39$, $U-B=-0.63$ compared to 8.12, +0.32, -0.57, respectively, from Table I. The difference is possibly due to the Be nature of the star either as a result of slight variability

TABLE II. Spectral classification of additional stars.

Star	R.A. (1900)	Dec.	Sp.	V	B-V	U-B	Ref.	Region	Notes
HD 48979	06 ^h 41 ^m .1	-07°14'	A1 V	9 ^m 49	+0 ^m 25	-0 ^m 67		S289	
HD 59966	07 27.3	-16 46	O9.5 V				(1)	S302	
HD 64315	48.2	-26 10	O6.5n	9.21	+0.22	-0.74		S311	
HD 64508	49.4	-25 58	O5	9.39	+0.11	-0.86		S311	
HD 69464	08 12.0	-35 19	O7f	8.84	+0.31	-0.61		G10	
CP -35°2209	15.1	-35 49	O8.5 V	10.19	+0.29	-0.66		RCW 20	
CP -35°2212	15.3	-35 50	O9.5 IV	9.17	+0.32	-0.67		RCW 20	
HD 74804	41.0	-40 55	B0 V					G15	
HD 76556	51.7	-47 14	O6	8.20	+0.41	-0.66		G21	
HDE 298377	09 20.6	-51 32	B1 IVn	10.27	+0.28	-0.66		G26	CP -51°2174
HD 90273	10 27.1	-57 09	O7	9.07	+0.17	-0.83	(2)	G29	
HD 90615	22.6	-56 49	B0 II	8.21	+0.25	-0.65	(2)	RCW 50	
CP -57°3781S	42.3	-58 08	O8	10.71			(3)	G32	
HD 97151	11 05.8	-59 33	B2 Ve					G37	†
HD 97222	06.3	-59 36	B0 II	8.81	+0.18	-0.76	(2)	G37	†
CP -59°5895	15 10.7	-59 35	B0.5 Ia	10.16	+0.90	-0.15		G49	
HD 142152	47.8	-54 29	B0 III	9.57	+0.35	-0.53		Lyngå 4	
HD 145217	16 04.6	-50 03	O8	9.96	+0.85	-0.57		BBW 30000	†
CP -51°9180	09.2	-51 43	B1 I	9.77	+0.94	-0.20	(4)	RCW 101	†
HD 147049	14.4	-52 29	B1.5 Ia	7.67	+0.29	-0.58	(4)	RCW 102	†
HD 149019	26.9	-49 34	A0 Ia	7.45	+0.88	+0.17		BBW 30402	†
HD 150197	34.3	-47 22	O9 III	9.51	+0.40	-0.57		BBW 30402	†
CD -38°11636	17 05.5	-38 22	O9:					G38	†
HD 155889	09.2	-33 37	O9 V	6.55	-0.02	-0.85		S10	
HDE 319699	12.8	-35 36	O7	9.63	+0.77	-0.25		S8	†CP -35°6932
HDE 319703A	13.1	-35 59	O6	10.71	+1.14	+0.04		S8	†CP -35°6933A
HDE 319702	14.2	-35 46	O9	10.13	+0.90	-0.13		S8	†CP -35°6940
HD 156738	14.2	-35 58	O7	9.37	+0.86	-0.16		S8	
HDE 319718	18.1	-34 06	O7	10.01	+1.59	+0.31	(5)	S11	IN NGC 6357
HD 158186	22.7	-31 27	O9.5 V					S13	
HD 166033	18 03.7	-23 40	B1 V	9.90	+0.20	-0.66		S32	
HD 314031	03.8	-23 38	B0.5 V					S32	CP -23°6899
HD 166107	04.0	-23 48	B1 V					S31	
HD 166192	04.4	-23 56	B2 V					S29	

Notes and references to Table II

A dagger (†) in the notes column indicates that the spectral type was determined from plates in the Radcliffe files (not taken by the writer).
 1. Sharpless, S., unpublished.
 2. Feinstein (1969).

3. Graham (1968).
 4. Huang *et al.*, (1966).
 5. Andrews, F. J., unpublished photometry based on observations from only one night.

(Schmidt-Kaler 1964) or of differences in the pass-bands of the photometers.

III. SPECTRAL CLASSIFICATION

The spectral classification was made on spectra with a dispersion of 86 Å mm⁻¹ at Hy (d camera) obtained with the two-prism Cassegrain spectrograph attached to the 1.88-m (74-inch) Radcliffe reflector. Existing spectra in the Radcliffe files were kindly made available by Dr. Thackeray for the classification of some of the stars, and spectra taken primarily for a radial-velocity program were also available. At least two spectra with a width of 0.5 mm taken on Kodak IIA-Ob plates were used for most of the stars although reference was also made to spectra with a dispersion of 49 Å mm⁻¹ at Hy in some cases. The classification was carried out by comparison with the Radcliffe collection of MK standard stars taken under the same conditions. Hill (1970, his Table II) lists the spectral types of the standards contained in this collection. Spectra of standard O5-8 stars were also available. No systematic errors were detected between classifications of the new

spectra and the spectra on file at Radcliffe or between these and published classifications.

The spectral types have been included in Table I. Those types in the table followed by an asterisk are not new determinations but have been taken from the literature. Spectral classifications for additional stars are given in Table II. The format of this table is identical to that of Table I with the exception that the eighth column gives a reference to the source of the photometry if it is not the catalogue of Blanco *et al.* (1968). The designation Lyngå 4 for one of the H II regions refers to the list of regions discovered by Lyngå (1965).

IV. OPEN CLUSTERS

Stars in five open clusters are included in Tables I and II. Table III lists these stars with their reddening and distance moduli obtained from the data given in Tables I and II. Intrinsic colors for each spectral type were taken from Johnson (1963), the absolute magnitude calibration used is that of Blaauw (1963), and the ratio of total-to-selective absorption was assumed to

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TABLE III. Stars in open clusters.

Cluster 1900 coordinates	Star	E_{B-V}		$(m-M)_0$	Notes
		MK	UBV		
NGC 2367 07 ^h 15 ^m 9 — 21°45'	HD 57370AB BD — 21°1881	0 ^m 36: 0.32	0 ^m 35 0.33	12 ^m .4: 12.5 12.5	(1)
Mean:					
NGC 2467 07 ^h 48 ^m 3 — 26°08'	HD 64315 HD 64568	0.54 0.43	0.52 0.43	13.0 13.7 13.4	
Mean:					
Stock 16 13 ^h 12 ^m 2 — 62°00'	HD 115455 CP — 61°35'76 CP — 61°35'79 CP — 61°35'81	0.53 0.57: 0.48 0.48	0.53 0.59: 0.52 0.50	11.6 11.8: 11.5 11.2 11.5 11.4 12.6 13.0 13.9:	Member?
Mean:					
Pismis 20 15 ^h 07 ^m 6 — 58°42'	HD 115316 CP — 61°35'87 CP — 61°35'98 MR 44 MR 45	0.49 0.56 1.01 0.90: ?	0.53 0.55	11.4 12.6 13.0 13.9: ?	
Mean:					
Pismis 24 17 ^h 18 ^m 7 — 34°15'	HD 134959 No. 11	1.21: 1.20:		11.3: 13.2:	13 ^h 11 ^m 5 — 61°54' 13 ^h 11 ^m 9 — 61°57'
Mean:					
	MR 54, HD 134877 MR 55	1.06 1.09		14.4 14.4	See text 15 ^h 07 ^m 1 — 59°28' 15 ^h 07 ^m 7 — 58°40'
Mean:					
	HD 319718 MR 72, HD 157504	1.91: 1.63:	1.87	9.7: 10.4:	(2) 17 ^h 18 ^m 5 — 34°06'
Mean:					
	HD 75991 HD 76535 HD 76556	0.41 0.70 0.73	0.42	11.8 11.9 11.5	
Mean:					
	MR 16, HD 76536	0.61 0.43	0.73	11.7 12.4	

Notes to Table III

1. The distance modulus was obtained assuming that the stars were of identical brightness (see Note 3 to Table I).
2. This cluster is possibly the "double star" referred to in the description of the nebula NGC 6337 (Dreyer 1888).

be 3. The reddening was computed both from the intrinsic color corresponding to the MK type (column 3) and from the UBV photometry alone (column 4) using the technique described by Crawford (1970).

Lodén (1965) and Lyngå (1970) have published data for stars in NGC 2467 and Stock 16, respectively, which are in good agreement with those in Table III. For Pismis 20, Lyngå (1968b) used the color-magnitude diagram to estimate a distance modulus of 13^m.2 in agreement with the modulus obtained here for star No. 11. If the distance modulus is 13^m.2, then HD 134959 must be an extremely luminous star ($M_V = -8.7$) assuming that it is a member of the cluster as seems to be likely from its position. Radial-velocity measurements (unpublished) indicate that its velocity is constant and similar to that of star No. 11. The spectrum does not show the characteristics which might be expected of a star of this luminosity. Further observations in excellent seeing conditions are required to improve the data on this star and the cluster as a whole.

Wolf-Rayet stars which may be members of three of the clusters are also listed in Table III with reddening and moduli derived from the data and relationships given by Smith (1968). These stars are identified by their MR numbers (Roberts 1962) and their co-

ordinates are listed in the notes column for comparison with the cluster positions. From the reddening and distance modulus, MR 44 is more probably associated with stars at the distance of CP — 61°35'98 than with Stock 16 (this may also be true of the H II region RCW 75). MR 45 is probably too faint to be a member of Stock 16 and MR 54 is probably too far away from Pismis 20 to be associated with it, but the membership of the other three stars with the clusters is probable. Also included in Table III are three OB stars from Tables I and II which may be responsible for exciting the nebula G21 along with the WR star MR 16. A comparison of the distance moduli derived from the OB stars and the WR stars in Table III reveals a systematic difference of about one magnitude in the sense that the WR stars appear to be further away. A similar result was noted by McCuskey (1970) in a comparison of the distributions of OB stars and WR stars. The clusters listed in Table III warrant further attention if only to improve the data on WR stars.

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Observations of $\lambda 4430$ in Reflection Nebulae

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Narrow-band filters have been used to isolate the diffuse interstellar feature at $\lambda 4430$ Å. Observations of three reflection nebulae indicate that, in both NGC 1435 (Merope) and IC 2177, the feature is formed within the nebula while it does not seem to be formed within IC 432.

THE diffuse interstellar absorption feature centered at $\lambda 4430$ Å has been studied by many people, but the explanation of its origin remains nearly as much a mystery as when it was first discovered. One of the characteristics of the absorption is that its strength is moderately well correlated with interstellar reddening. This has led most investigators to postulate that the feature is physically associated with the interstellar dust grains that cause the reddening. In an attempt to verify this connection, as well as to confirm the idea that the dust in reflection nebulae is typical of interstellar dust, measurements have been made of the strength of the $\lambda 4430$ feature in several reflection nebulae and in their illuminating stars.

OBSERVATIONS

The measurements were made in December 1969 with the No. 1 36-inch telescope at Kitt Peak National

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Observatory using a conventional photoelectric photometer. The $\lambda 4430$ feature was isolated by means of three narrow-band (half-width ≈ 20 Å) filters with nominal centers at $\lambda 4410$, $\lambda 4430$, and $\lambda 4450$ Å and a wider-band (half-width ≈ 95 Å) filter centered at $\lambda 4430$ Å. The transmission curves of the filters (at room temperature $\approx 27^\circ\text{C}$) are shown in Fig. 1. The use of these four filters gives two semi-independent measures of the strength of the $\lambda 4430$ feature. The combination of the wider filter with the narrow filter, both centered at $\lambda 4430$ Å, gives an index which should be very similar to that used by Kristenson and Rudkjöbing (1965) and by Baerentzen *et al.* (1967) for stellar observations. The combination of the three narrow filters gives an alternative index which, it was hoped, would be less dependent on spectral type and continuum slope (interstellar reddening). Two other filters, centered at $\lambda 4320$ and $\lambda 4510$ Å, were used to determine differences in continuum slope between star and nebula, i.e., to measure the variation of the scattering efficiency with wavelength. The phototube used was an RCA 1P21, the output of which was measured by a standard Kitt Peak integrator and associated electronics.